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TIME HISTORY ANALYSIS OF HIGH-RISE BUILDINGS WITH OUTRIGGER AND BELT TRUSS SYSTEMS

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Abstract - *The seismic performance of high-rise buildings is a major consideration in structural engineering, particularly under strong ground motion. This study investigates the influence of outrigger and belt truss systems on the dynamic behavior of tall structures using time history analysis. Three analytical models of a reinforced concrete building with a total height of 48.25 m (G+15) were developed in ETABS. The first model represents a conventional frame without supplemental systems, the second incorporates a belt truss, and the third employs an outrigger truss. Seismic response evaluation was carried out using the El Centro earthquake ground motion record. Comparative assessment was performed with respect to lateral displacement, inter-story drift, and base shear. The results demonstrate that the integration of outrigger and belt truss systems significantly improves the lateral stiffness and overall seismic resistance of the structure, with the outrigger truss configuration exhibiting superior performance. The study emphasizes the practical applicability of these structural systems in enhancing the resilience and serviceability of high-rise buildings subjected to earthquake loading.*

Key Words: **Time history analysis, high-rise buildings, outrigger system, belt truss, seismic performance, ETABS, El Centro earthquake.**

1. INTRODUCTION

1.1 Background of High-Rise Building Design Challenges

The rapid growth of urbanization and the scarcity of land have significantly increased the demand for vertical expansion through high-rise buildings. While these structures serve as efficient solutions for accommodating population and commercial activities, they also pose unique engineering challenges, particularly in resisting lateral loads generated by wind and seismic events. Unlike low-rise structures where gravity loads dominate the design process, tall buildings are largely governed by their lateral stiffness and stability requirements (Taranath, 2016). Excessive lateral displacements and inter-story drifts not only compromise structural safety but also affect the serviceability of non-structural components. Conventional structural systems such as rigid frames often fail to provide adequate resistance at greater heights, thereby necessitating the integration of advanced lateral load-resisting mechanisms. These complexities make the design of high-rise buildings an evolving domain in structural engineering, demanding a balance between safety, economy, and functionality.

1.2 Importance of Seismic Performance Evaluation in Tall Structures

Earthquake-induced forces are among the most critical factors influencing the design of high-rise buildings. Unlike static wind loads, seismic loads are dynamic, irregular, and highly unpredictable in nature, which makes their impact particularly severe on tall structures (Chopra, 2017). The height, slenderness, and mass distribution of high-rise buildings amplify their susceptibility to ground motion, often leading to resonance effects, structural instability, and even progressive collapse if not adequately addressed. Seismic performance evaluation is therefore indispensable for ensuring resilience and minimizing damage during strong ground motions. Analytical techniques such as time history analysis provide a realistic measure of the building's response by directly incorporating ground motion records (Kalkan & Kunnath, 2006). This enables engineers to assess structural parameters such as displacement, drift, and base shear more accurately compared to traditional static methods. Given the increasing frequency of earthquakes in urban regions, enhancing the seismic resilience of tall buildings is not just a structural requirement but a necessity for safeguarding human lives and reducing economic losses.

1.3 Role of Outrigger and Belt Truss Systems in Structural Engineering

To overcome the limitations of conventional systems, structural engineers have developed innovative solutions such as outrigger and belt truss systems, which have proven to be highly effective in controlling lateral displacements in high-rise buildings. The outrigger system connects the building's central core to the outer columns through stiff horizontal members, effectively transforming the entire building into a deep cantilever structure (Zhang & Taranath, 2010). This mechanism enhances the overall stiffness and reduces overturning moments by engaging exterior columns in resisting lateral loads. Similarly, belt trusses act as horizontal ties around the perimeter of the building, distributing lateral forces and improving load-sharing among columns (Choi & Joseph, 2011). When combined, these systems provide a synergistic effect, significantly improving both stability and structural efficiency. Studies

have shown that buildings equipped with outrigger and belt truss systems exhibit reduced lateral displacement and drift, thereby enhancing both safety and serviceability under seismic loading conditions (Hander Kamp & Bakker, 2003). Thus, these structural innovations have become integral components in the modern design of tall buildings, bridging the gap between architectural ambitions and engineering feasibility.

2. LITERATURE REVIEW

2.1 Previous studies on seismic performance of high-rise buildings

Research on the seismic behavior of high-rise buildings has evolved from simplified static approaches to advanced dynamic and performance-based assessments, reflecting the complex interaction between tall structural forms, mass distribution, and irregular excitation from earthquakes. Foundational studies emphasize that tall structures respond to seismic input with coupled translational and torsional modes, making accurate dynamic analyses — notably elastic and inelastic time-history procedures — essential for realistic assessment of demands such as roof drift, inter-story drift, and base shear (Jia et al., 2022). Recent reviews and parametric investigations further underline that earthquake records with distinct frequency content (for example, near-fault pulse-type motions versus broadband records) produce markedly different responses in tall frames, and that the choice and scaling of ground-motion records strongly influences the predicted peak demands and mode participation factors. Thus, contemporary literature recommends time-history analyses for performance verification of tall buildings, especially when supplemental lateral systems or irregular geometries are present.

2.2 Application of outrigger systems in lateral load resistance

The outrigger system has been extensively studied as an efficient mechanism to increase lateral stiffness and reduce overturning in tall buildings by mobilizing exterior columns to participate in resisting lateral loads through stiff horizontal links to the core. Early analytical and design investigations established the basic mechanics and optimal layout principles — demonstrating that well-positioned outriggers can significantly reduce top displacement and inter-story drift by coupling the bending of the core with the tension/compression action of perimeter columns (Hoenderkamp & Bakker, 2003). Subsequent parametric and optimization studies have examined the influence of outrigger location, number, depth, and stiffness on performance, showing that outrigger effectiveness depends on story stiffness distribution, core-to-perimeter stiffness ratio, and the presence of flexible foundations; optimal placement often lies at levels corresponding to abrupt changes in mass or stiffness. Recent comparative and cost-oriented studies also report that outriggers can achieve large reductions in lateral displacements with modest additional material cost when judiciously designed, reinforcing their adoption in modern tall-building practice.

2.3 Effectiveness of belt trusses in reducing displacement and drift

Belt truss systems, frequently used in conjunction with outriggers, serve as peripheral horizontal diaphragms that tie exterior columns together and improve global stiffness and load redistribution. The literature characterizes belt trusses as particularly effective in reducing floor-level drift and controlling differential displacement between the core and façade, thereby improving serviceability and protecting non-structural components. Comprehensive reviews and design guides summarize that belt trusses are most beneficial when they encircle the building at transfer levels or mechanical floors, where they can redistribute bending moments and engage multiple columns, resulting in more uniform column forces and reduced local buckling risk. Empirical and numerical studies further indicate that belt trusses can complement outriggers by improving the efficiency of column-core coupling and that their combined use often yields superior performance compared to either system alone; however, the magnitude of benefit varies with plan regularity, aspect ratio, and the stiffness contrast between core and perimeter frames.

2.4 Limitations in existing research

Despite the large body of work, several limitations persist that constrain the universal applicability of published findings. First, many parametric studies assume idealized geometry and linear elastic material behavior, whereas real tall buildings exhibit geometric irregularities, nonlinearity, and complex interaction with non-structural elements that can alter demand patterns. Second, a significant portion of existing investigations use a limited set of ground-motion records or simplified scaling procedures; this can bias conclusions because record selection and scaling critically affect time-history outcomes. Third, comparative studies that evaluate outriggers and belt trusses often neglect practical considerations such as constructability, service-integration at belt/outrigger levels, and the effect of foundation flexibility — all of which can materially influence system performance. Finally, although recent experimental and large-scale numerical studies have advanced understanding, data on combined systems under near-fault pulse motions and multi-directional excitations remain comparatively sparse, leaving open questions about worst-case performance scenarios for modern irregular tall buildings.

2.5 Research contributions of the present study

In light of the gaps summarized above, the present study contributes to the literature by providing a focused, comparative time-history investigation of three ETABS

models of a 48.25 m (G+15) reinforced concrete building: a conventional frame (control), a frame with a belt truss, and a frame with an outrigger truss. By applying realistic El Centro ground motion records in elastic time-history analyses and directly comparing lateral displacement, inter-story drift, and base shear across the three configurations, this research addresses the need for head-to-head performance comparisons using consistent modeling assumptions and record application. Furthermore, by documenting relative reductions in key demand parameters and discussing practical implications for design placement and system selection, the study aims to offer actionable insights for practicing engineers and to identify directions for subsequent nonlinear, multi-record, and constructability-aware investigations. These targeted contributions situate the work amid both established theory and contemporary practice.

3. METHODOLOGY

3.1 Software Used

The structural analysis in this study was conducted using ETABS (Extended Three-Dimensional Analysis of Building Systems). ETABS is widely employed in both research and practice due to its ability to model complex geometries, assign material properties, and simulate realistic load conditions. It incorporates finite element techniques, making it highly reliable for dynamic analyses such as time history evaluation. The software also supports compliance with international and Indian standards, ensuring accurate and code-compatible results.

3.2 Building Model Details

The building selected for this research is a G+15 reinforced concrete (RC) structure with an overall height of 48.25 m. The geometry and sectional details were defined according to conventional design practices in India. Standard beam, column, and slab cross-sections were adopted, and the plan layout was kept symmetrical and regular to avoid irregularity-induced effects on seismic performance. The building core was modeled to represent the vertical load-resisting system, while the lateral load-resisting systems were varied in different models to enable comparative assessment.

Table-1: Building Model Details

S.No	Parameter of Building	Values
1	Cross section of Beam	300mm * 450mm
2	Cross section of Column.	325mm * 550mm
3	The thickness of the Slab.	135.00 mm
4	Floor Height of GF	3250 mm
5	Height of G+15	48250 mm
6	Floor Height except GF	3000 mm
7	Plan Area	30m*24m

3.3 Configurations Studied

To examine the role of outrigger and belt truss systems, three structural configurations of the same building were developed in ETABS:

1. **Model 1: Conventional Frame-** A standard reinforced concrete frame structure without any additional lateral stiffening systems, representing the baseline condition.
2. **Model 2: Frame with Belt Truss-** The building was integrated with a belt truss system at a designated storey. The belt truss ties the perimeter columns together, thereby improving their collective resistance to lateral forces.
3. **Model 3: Frame with Outrigger Truss-**The model incorporated an outrigger truss connecting the central core to the exterior columns. This arrangement enhances stiffness by mobilizing the perimeter columns to act as levers against overturning moments.

These three models enabled direct comparison of structural responses under identical seismic inputs.

3.4 Loading Conditions

The structural models were subjected to various load combinations in compliance with Indian Standard codes. The loading details are as follows:

- Dead Load: As per IS 875 (Part 1: 1987).
- Live Load: As per IS 875 (Part 2: 1987).
- Seismic Load: As per IS 1893 (Part 1: 2016).

These loads were combined according to code-specified load combinations to reflect realistic design scenarios.

Table-2: Load on Models.

S.No	Name of Load	Value
1	Deal Load	As Per IS Code 875 Part 1
2	Live Load	3 KN/m3
3	Floor Finishing Load	1.25 KN/m3
4	Seismic Load	As per IS Code 1893 Part-1:2016

3.5 Seismic Input

For the dynamic analysis, the El Centro earthquake ground motion record was used as the seismic input. This ground motion has been extensively employed in seismic research due to its strong motion characteristics. The accelerate gram was scaled to match the design response spectrum specified in IS 1893:2016, ensuring compatibility with the Indian seismic design framework. By applying actual earthquake data, the time history analysis provided an accurate picture of the building's behavior under realistic seismic conditions.

Table-3.4: Seismic Load Parameter

S.No	Seismic Parameter	Value
1	Seismic Zone	0.16 (Third Zone-Lucknow)
2	Importance Factor	1.50
3	Soil Type	Medium Soil
4	Response Reduction Factor	5 (Special Moment Resisting Frame)

3.6 Performance Parameters

The performance of the models was assessed based on three critical parameters:

- **Lateral Displacement:** Represents the overall sway of the building under seismic action. Excessive displacement can compromise structural stability and occupant comfort.
- **Inter-Story Drift:** Indicates the relative horizontal displacement between consecutive floors. This parameter is crucial as it directly affects both structural safety and non-structural components such as partitions and cladding.
- **Base Shear:** Reflects the total horizontal seismic force transmitted to the foundation. It is a measure of the overall seismic demand on the structure and helps assess the efficiency of the lateral load-resisting system.

Together, these parameters provided a comprehensive evaluation of how conventional, belt truss, and outrigger systems perform in controlling seismic responses.

4. RESULTS AND DISCUSSION

4.1 Comparative Performance of the Three Models

The seismic performance of the three building models—conventional frame, frame with belt truss, and frame with outrigger truss—was evaluated through time history analysis under El Centro earthquake excitation. The results clearly indicate that the inclusion of supplemental structural systems significantly improves the seismic behavior of the high-rise building. The conventional frame exhibited the highest values of lateral displacement, inter-storey drift, and base shear, demonstrating the limited capacity of traditional systems

4.2 Lateral Displacement Trends

The lateral displacement profile of the three models highlights the benefits of introducing belt and outrigger systems. The conventional frame displayed substantial displacement at the roof level, indicating vulnerability to excessive sway during strong seismic excitation. Incorporation of the belt truss reduced the displacement significantly by mobilizing the perimeter columns to resist lateral loads.

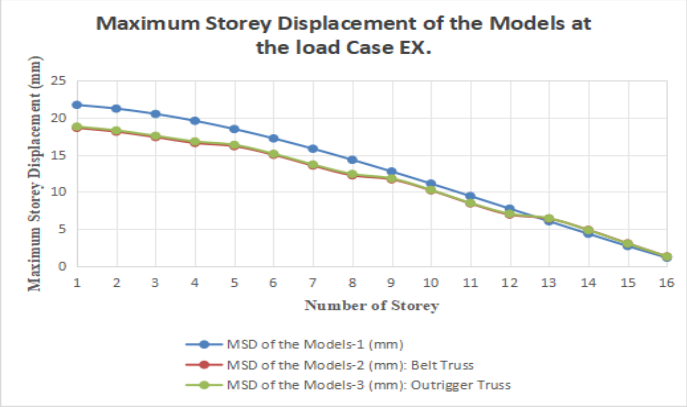

Figure-1: Maximum Storey Displacement of the Models at the load Case EX.

4.3 Neural Periods

The fundamental period of a structure denotes the minimum natural period of vibration experienced by the structure under external forces. This period is determined by various factors such as the mass, stiffness, and geometry of the structure. As per IS Code 1893 part-1:2016, the natural period for structures up to G+20 should fall within the range of 0.05 seconds to 2.00 seconds, while structures up to G+30 should have a period exceeding 3.00 seconds. Here the total floor of the structure is G+15, so the total value of the natural period should be less than 2.00 second. The table and graph depicting the natural period are provided below for reference.

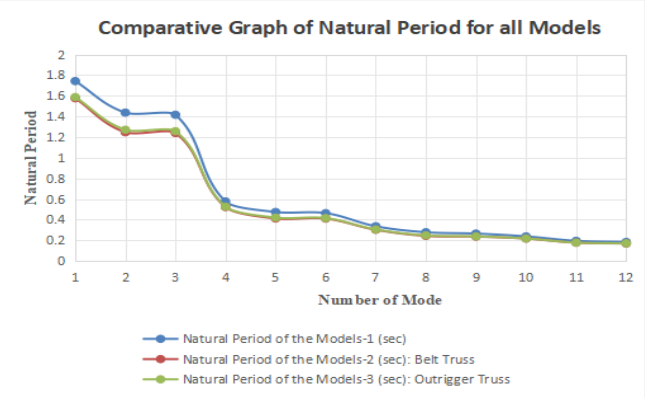

Figure-2: Comparative Graph of Natural Period for all Models.

4.4 Base Shear Response

Base shear represents the total horizontal seismic force transferred to the foundation. The comparative analysis revealed that while the belt truss system moderately reduced base shear, the outrigger truss system achieved a more pronounced reduction. This reduction is attributed to the enhanced stiffness of the outrigger system, which limits the overall deformation of the structure and consequently reduces the seismic demand on the foundation.

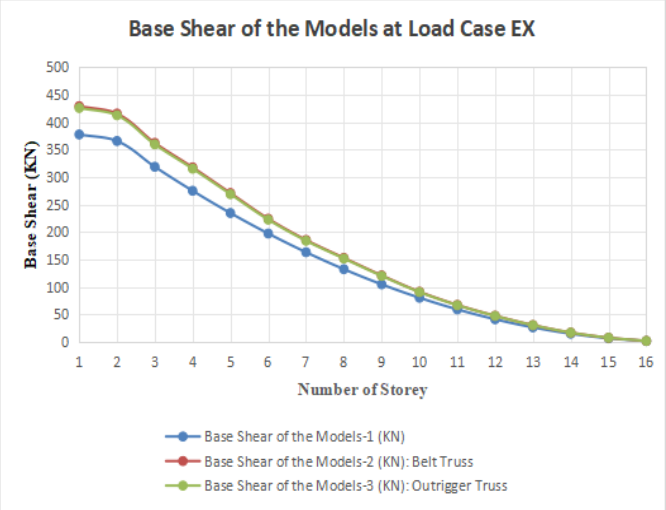

Figure-3: Base Shear of the Model at Load Case EX.

4.5 Practical Implications for Structural Engineers

The results of this study hold significant implications for practicing structural engineers and urban planners. The findings confirm that reliance on conventional frames alone may not be sufficient for high-rise buildings located in seismic regions, as excessive displacements and drifts can compromise both safety and serviceability. The belt truss system emerges as a practical solution for moderate improvements, especially where architectural and space constraints limit the use of larger structural cores. However, for buildings exceeding certain height thresholds or located in high seismic zones, the outrigger truss system is a more reliable and effective choice. Its ability to mobilize exterior columns in resisting overturning effects ensures enhanced resilience, reduced damage potential, and greater occupant comfort. The integration of these systems into design practice not only improves structural safety but also contributes to more economical use of materials compared to oversized shear walls or heavily braced frames.

5. CONCLUSION

This research has demonstrated the effectiveness of outrigger and belt truss systems in enhancing the seismic resilience of high-rise buildings. Through time history analysis of a G+15 reinforced concrete structure, it was observed that the conventional frame alone is inadequate in controlling excessive displacements and drifts under strong ground motions. The introduction of a belt truss system improved performance by mobilizing the perimeter columns and reducing structural sway, but the outrigger truss system delivered superior results. By linking the building core with exterior columns, the outrigger system significantly reduced lateral displacement, controlled inter-storey drift within permissible limits, and lowered base shear demand on the foundation. These findings affirm that outrigger systems, and to a lesser extent belt trusses, represent effective structural solutions for seismic-prone regions. For practicing engineers, the study emphasizes the importance of integrating such systems into the design of tall buildings, not only for structural safety but also for long-term serviceability and occupant comfort. Ultimately, this work contributes to the growing body of knowledge in earthquake-resistant design and supports the development of safer, more resilient urban skylines.

6. LIMITATIONS

Although this study provides meaningful insights into the seismic performance of high-rise buildings with outrigger and belt truss systems, several limitations must be acknowledged. The analysis was restricted to numerical modeling in ETABS, without experimental or shake-table validation. While software simulations provide reliable trends, they may not fully capture real-world uncertainties such as material variability, construction imperfections, and boundary condition irregularities. The study also employed a single ground motion record—El Centro earthquake—for time history analysis. Although this record is widely used in seismic research, relying on a single input may limit the generalizability of results, as earthquake characteristics vary significantly in terms of frequency content, duration, and intensity. Furthermore, simplifying assumptions such as material homogeneity and idealized support conditions were adopted, which may not represent actual structural behavior under severe seismic loading. In addition, only limited configurations of belt truss and outrigger systems were examined, whereas in practice, variations in their number, placement, and geometry can greatly influence performance. These limitations highlight the need for broader parametric studies and experimental validations before extending the findings directly into design recommendations.

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